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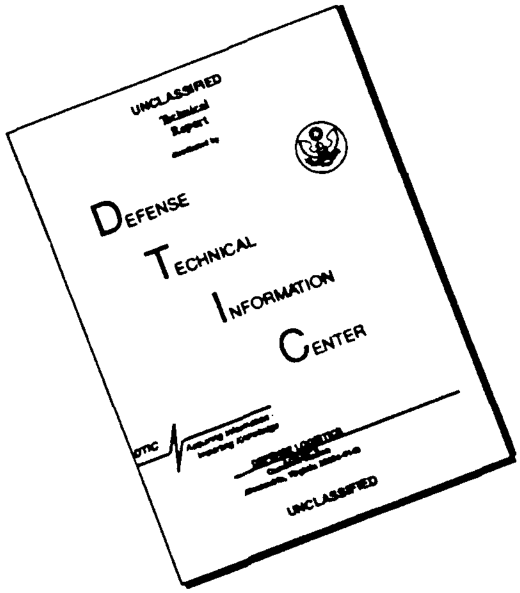

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SECOND INTERNATIONAL CONGRESS ON
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An Inferential Treatment of Resonance Scattering from Elastic Shells

M.F. Werby
NRL, Numerical Modeling Branch, Stennis Space Center, MS 39529
and
H. Überall
The Department of Physics, The Catholic University of America, Washington D.C. 20064

Abstract

One can extract both the existence and nature of resonances on elastic shells by direct measurement of surface vibrations or one may infer this information by examining various aspects of far field scattering via back scattered echo's and residual bistatic angular distributions. The origin of the inferential method is contained in the prodigious work of Überall[1,2] over the past decades. In this study the later technique is taken and an analysis for recently studied resonances is presented. Use is made of the recently formulated acoustic background for elastic shells[3-5] which makes it possible to examine residual back scattered echo's characterized by pure resonance effects. One observes the lowest order symmetric and antisymmetric model or Lamb resonances as well as water borne and pseudo-Stoneley resonances[6] and the higher order Lamb modes A_i and S_i where i=1,2,3... Use of partial wave analysis will be made to investigate several relevant cases which infer the nature of the resonances.

Introduction

A direct approach advocated by Hickling[7] to examine the nature of resonances pertains to measurement of the vibrations on the surface of an object. Such measurements are generally not feasible especially for remote targets so that a systematic method has been worked out that enables researchers to infer information from certain features from the far field scattered signal. Our aim here is to discuss some of the methodology used to extract information concerning resonances and in particular to discuss observations of recently studied phenomena. A discussion of a resonance scattering theory in the time domain[8,9] is outlined since we will make use of it in what follows. The correct acoustical background for an elastic shell has been developed[3-5] and it now allows one to make proper use of partial wave analysis to determine the nature of specific resonances and so a limited discussion of the new background is presented here with examples. A partial wave analysis is then used to interpret the resonances. We will focus on water borne resonances observed at coincidence frequency (pseudo-Stoneley resonances) both in the time and frequency domains and on other kinds of water borne waves that occur on elastic shells particularly at higher frequencies. We will emphasize the pseudo-Stonely resonances which are narrow in ka space and occur over a limited frequency region about coincidence frequency, the point at which the flexural resonances begin to manifest themselves. The flexural resonances are very broad and fairly weak at inception though they become narrower and increase in magnitude with increasing frequency. We illustrate, in addition, that there are also other water borne waves that increase in importance with increasing frequency and are also more significant for lower material densities and thinner shells.

The correct acoustical background for elastic shells

In several works Überall and colleagues[1,2] determined that in the absence of a resonance an elastic solid behaves like a rigid scatterer. This was referred to as the " background " for the elastic solid. Subsequently Überall et al.[10,11] employed that background for elastic shells although such a choice is not in general adequate. It has been

demonstrated that for shells a rigid background is adequate for high frequencies while a soft background is adequate for very thin shells at the lower frequency end.[12,13] However, for a large number of circumstances, neither is adequate. The correct background for shells has recently been published[3-5] and is based on implementing relevant conservation principles, use of entrained mass and a postulate that determines the surface displacement on a shell in the absence of a resonance. We will demonstrate the effectiveness of the new background for an Aluminum shell of 2% thickness calculated for a ka from 0 to 120. Fig. 1a illustrates the back scattered response for the shell. Fig. 1b is the response minus a soft background which is a reasonable background for the very low frequency region but inadequate otherwise. Fig. 1c is the response minus the rigid background which is never very good in terms of isolating the resonances though it improves with increasing frequency. Finally, the new background is illustrated in Fig. 1d and is clearly very good through out the frequency range. In the figures there is a large return centered about ka=72. This is the region about coincidence frequency. In the next section we will use a partial wave analysis for a similar scatterer to show the presence of two types of waves.

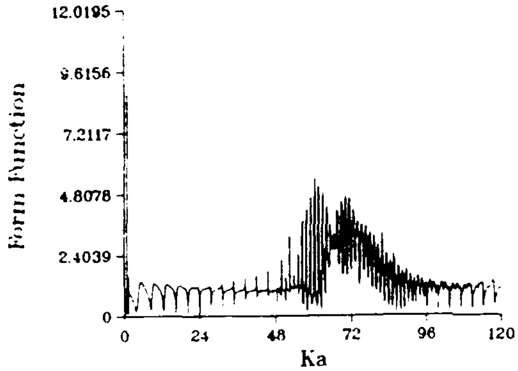


Fig. 1a Backscatter from 2% Al Shell,

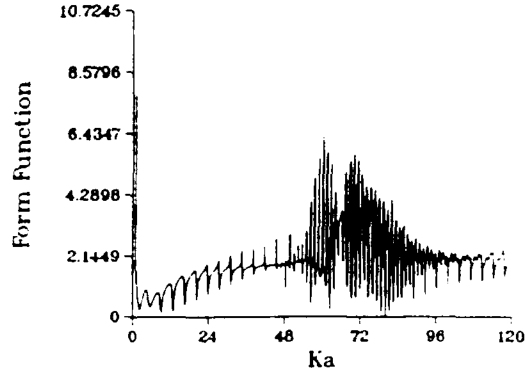


Fig. 1b Backscatter minus soft background.

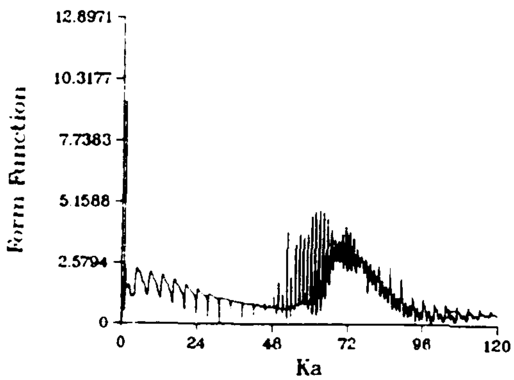


Fig. 1c Backscatter minus rigid background.

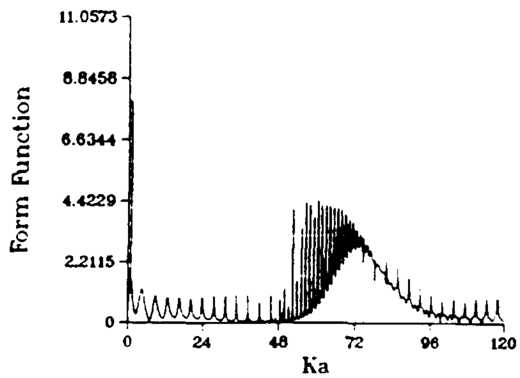


Fig. 1d Backscatter minus new background.

Partial wave analysis

If one subtracts the correct background from the elastic response then by definition one is left with the "pure" resonance response. Resonances excited on bodies of canonical shape usually correspond to circumferentially excited waves which for spheres have a unique wave number. To be sure, this fact can be obscured by, for example, broadly overlapping partial waves; but none the less by plotting the residual partial wave component which is here referred to as a partial wave analysis-can be very revealing. There are two ways to perform a partial wave analysis: one can fix the mode number N and plot the residual response with respect to ka. On the other hand one can fix ka and plot the partial wave form function with respect to mode number N. The first of these approaches is the most commonly used but it will be demonstrated that the second approach offers a powerful interpretative tool. The second approach will be referred to as a full partial wave analysis (FPWA) to distinguish it from the first case and because it involves all the partial waves for any fixed value of ka. We

examine back scatter signals from a 2.5% thick steel shell for ka=20 to 60. Fig. 2a illustrates mainly the region about coincidence frequency centered about ka=44. We can better understand what is happening be subtracting the new background to leave Fig. 2b which illustrates a series of spikes as well as what appears to be an envelop of some sort. We can determine what is happening be performing a FPWA at one of the lower spikes at Ka=31, an intermediate value at ka=37 and a higher value at ka=51. The analysis is illustrated in Fig. 3a, 3b, and 3c respectively. In each of the figures we see the presence of two waves. In the lowest two cases we observe a sharp well defined subsonic wave, and a weak broad sonic wave. Since we know that this takes place at about coincidence we infer that the broad wave represents the inception of a flexural resonance. We know from scattering from flat plates evacuated on one side and fluid loaded on the other that water borne waves (subsonic) exist at coincidence frequency and are referred to as Stoneley waves[15]. Thus we infer (in analogy with the flat plate case) that that subsonic sharp peak is associated with a Stoneley wave on a flat plate and thus is a pseudo-Stoneley resonance. We see from Fig. 3c that at some point the waves seem to merge but actually what happens is that the pseudo-Stoneley wave dissipates as it reaches the speed of sound of the fluid and another type of water borne wave begins to grow and to maintain prominence with increasing frequency. We will discuss the case below. We can also perform a study of the phase velocities of the two waves. The results are illustrated in Fig.4 (associated with the pseudo-Stoneley resonance) and Fig. 5 (the phase velocity associated with a flexural resonance). Note that the pseudo-Stoneley wave is of limited range and is mainly subsonic.

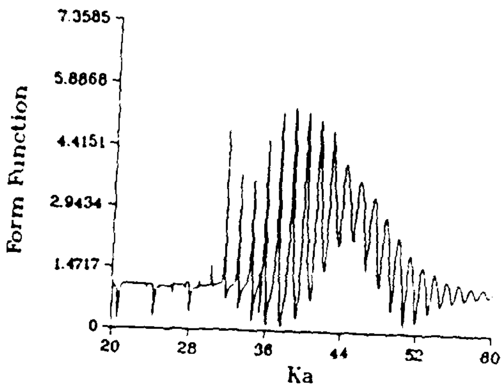


Fig. 2a Backscatter from 2.5% steel shell.

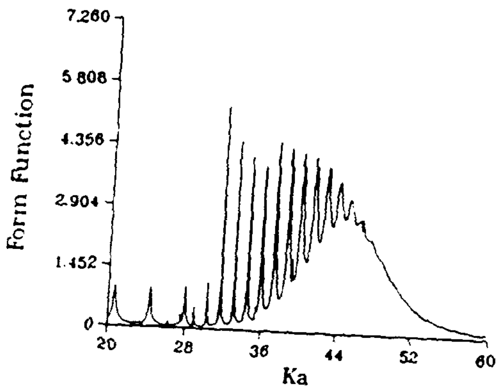


Fig. 2b Backscatter minus new background.

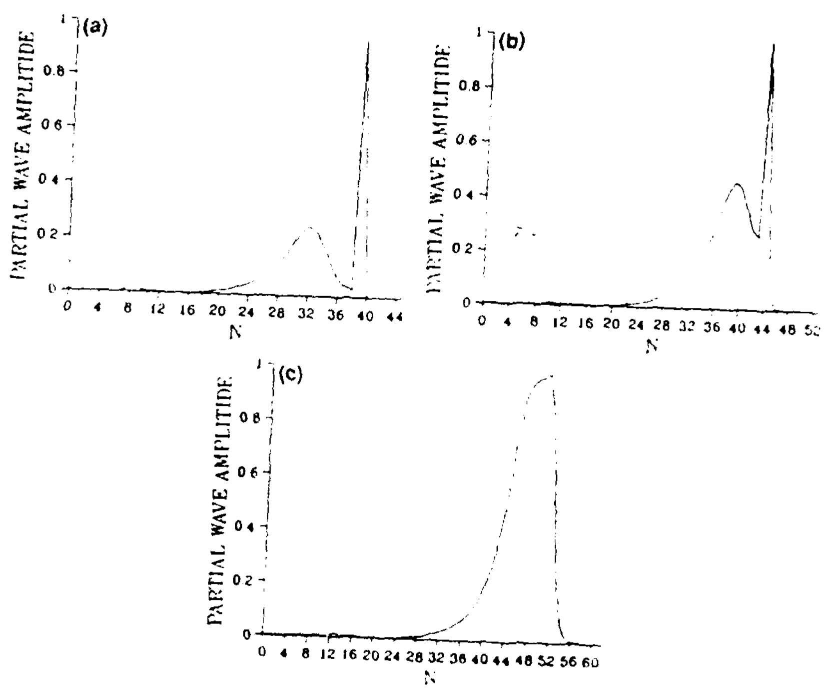


Fig. 3 Partial wave analysis for ka a) 31, b) 36, c) 51

Time Domain Resonance Scattering Theory

The partial wave series that emerges from normal mode theory for separable geometries can be represented in distinct partial waves or modes. It has been shown[1,2] that a representation due to a distinct mode(n) can be written in the form

$$f_n(\theta) = \frac{2}{ka} e^{2i\xi_n^{(r)}} \left\{ \frac{(\frac{1}{2})\Gamma_n^{(r)}}{\chi - \chi_n^{(r)} + (\frac{i}{2})\Gamma_n^{(r)}} + e^{-i\xi_n^{(r)}} \operatorname{Sin}\xi_n^{(r)} \right\} \qquad (1)$$

where $\chi = ka$, $\chi_n^{(r)}$ is the nth resonance and $(\frac{1}{2})\Gamma_n^{(r)}$ the half − width.

Where $e^{2i\xi_n^{(r)}} = -\dfrac{h_n^{(2)'}(x)}{h_n^{(1)'}(x)}$

Here, the factor 2n+1 is absorbed in the expansion coefficient. For the pulse form a continuous wave (cw) ping is used which corresponds to a very broad frequency range. For each time domain modal component one has that

$$\operatorname{Re} \int_{-\infty}^{\infty} \frac{(\frac{1}{2})\Gamma_n^{(r)}}{\chi - \chi_n^{(r)} + (\frac{i}{2})\Gamma_n^{(r)}} e^{-ixs} dx = 2\pi (\tfrac{1}{2})\Gamma_n^{(r)} \operatorname{Sin}(\chi_n^{(r)} s) e^{-(\frac{1}{2})s\Gamma_n^{(r)}} . \qquad (2)$$

That is, at a resonance the time domain solution is simply the product of the half-width times a sinuosoidal function times an exponential damping factor. From the time domain solution for a nest of resonances (N-m) for a cw ping, one obtains the form

$$p(s) \approx 2\pi \sum_{n=m}^{N} (\tfrac{1}{2})\Gamma_n^{(r)} \operatorname{Sin}(\chi_n^{(r)} s) e^{-(\frac{1}{2})s\Gamma_n^{(r)}} . \qquad (3)$$

The remaining contributions from backscatter are small due to phase averaging.

It is assumed that calculations are performed in a resonance region for which the resonance widths are fairly constant and the resonance spacing is fairly uniform[8,9]. This assumption leads to the important expression

$$P(s) \approx 2\pi 2^M (\operatorname{Sin}(\chi_{ave}^{(r)} S) \{\operatorname{Cos}(\Delta\chi_{ave}^{(r)} s / 2)\}^M e^{-s\Gamma/2}, \qquad (4)$$

$$\text{where } \chi_{ave}^{(r)} = \frac{1}{2M} \sum_{i=n}^{n+2M} \chi_i^{(r)} .$$

Here one sets n-m=2M. It is seen from the above expression that the half-width is associated with the decay of the response in the time domain solution. When the number of adjacent resonances (2M) sensed increases, the return signal becomes more sharply defined and the envelope function (the beats) are more enhanced and clearly defined Finally, for larger carrier frequencies, the signal is more oscillatory within the envelope.

Time Domain Back Scatter at Coincidence Frequency

Flexural waves do not yield resonances from fluid-loaded shells until the phase velocity of the flexural wave is about equal to the speed of sound in the ambient fluid. The value in frequency for which this happens is referred to as the coincidence frequency ; however, some subsonic fluid-borne waves produce sharp[8,9,14,15] resonances below coincidence frequency. These waves are referred to as pseudo-Stoneley waves and the related

resonances as pseudo-Stoneley resonances.[8,15] The pseudo-Stoneley resonances are well defined in partial wave space; they usually correspond to only one partial wave mode number and a very narrow half-width with a dispersive phase velocity, which approaches the speed of sound in the fluid with increasing frequency. The pseudo-Stoneley resonances diminish in significance at the point where the flexural resonances begin to dominate. It can be determined that a phase change occurs in the pressure field in the transition region from subsonic to supersonic. This change accounts for the envelope of the resonance curve at coincidence frequency where the waves are in phase until coincidence and are out of phase afterwards. Our interest here is in examining the time domain response, since one expects the conditions previously described to be partially met over a broad frequency range and thus to yield a strong coherent response with a carrier frequency in the neighborhood of the frequency at coincidence. Accordingly, the case of cw pings for two examples - for which coincidence resonances are expected to arise - is examined. This is certainly suggested by the strong responses in Figs. 6b and 7b at the ka values 113 and 87, respectively, for steel and WC. Further, in this analysis the Mindlin-Timoshenko [16] thick plate theory is used to determine the value for which the flexural phase velocity will equal the speed of sound in water. The phase and group velocities are determined from flat plate theory which proves to be quite reliable in predicting the phase velocity for the curved surfaces of the spheres at coincidence frequency.

The time domain calculations are now examined. The first example is a steel shell of 1% thickness. In this case a well-defined envelope (illustrated in Fig. 6a) with pronounced oscillations within the envelope is consistent with Eq. 4. The enhancement due to the factor 2^M is obvious. The group velocity can be obtained from the peak-to-peak distance of the adjacent envelopes. The result leads to a value of 2.23 km/sec. Both flexural and pseudo-Stoneley resonances compete in this region. A mixture of pseudo-Stoneley waves, as well as flexural waves must be leaking into the fluid. For flexural waves, the group velocity is 2.53 km / sec at coincidence frequency with a range between 2.44 and 2.68 km / sec. over the ka range of 100-140, where the strong flexurals are significant. In that range the phase velocity varies from 1.37 to 1.58 km/sec. The values of the extracted group velocity does not agree well with the flexural group velocity ; the discrepancy is 12%. This variation suggests that in the time sequence the flexural resonances are of little importance for the time sequence presented here. The group velocity of the pseudo-Stoneley waves for this case has been determined[14] to be 2.16 km / sec based on plate theory. The phase velocity is in the range from 88% to 98% of the speed of sound in the fluid. This value of group velocity is within 3% of the extracted value from the time domain solution. Moreover the pseudo-Stoneley resonances have very narrow widths while the flexural resonances are quite large. The conditions in the previous section would indicate that the flexural resonances would rapidly dampen due to the large half-widths while the pseudo-Stoneley resonances would attenuate slowly in time. Thus, based on the similarity of the extracted group velocity and that of the pseudo-Stoneley wave and the conditions in the previous section on level widths, one may conclude that the time domain calculations in Fig. 6a represent pseudo-Stoneley resonances. A similar argument holds for WC for Fig. 7a.

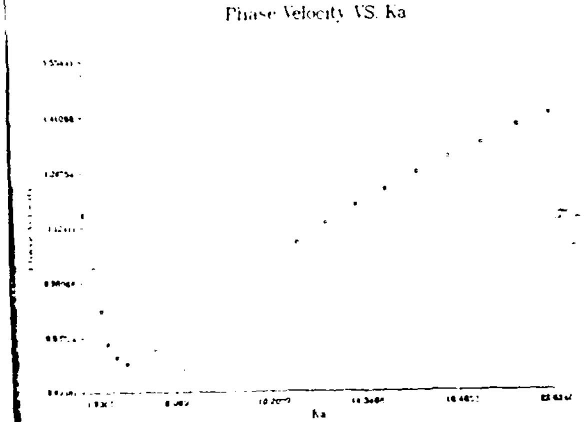


Fig. 4 Phase velocity for pseudo-Stoneley resonance.

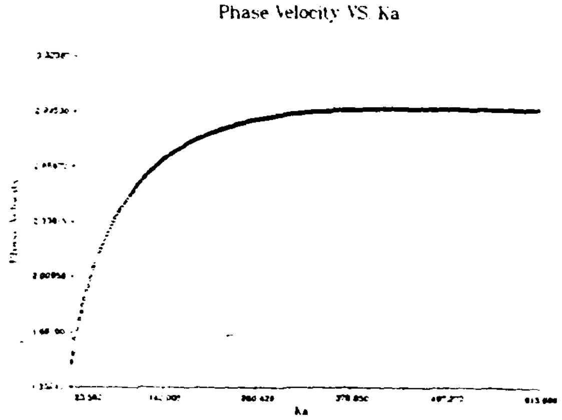
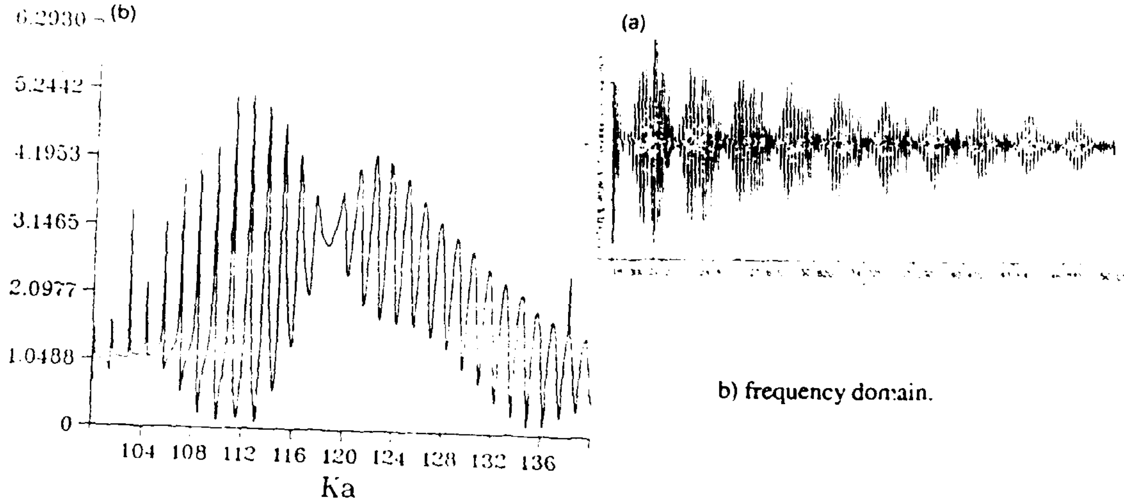


Fig. 5 Phase velocity for flexural resonance.

Pure Water borne Waves

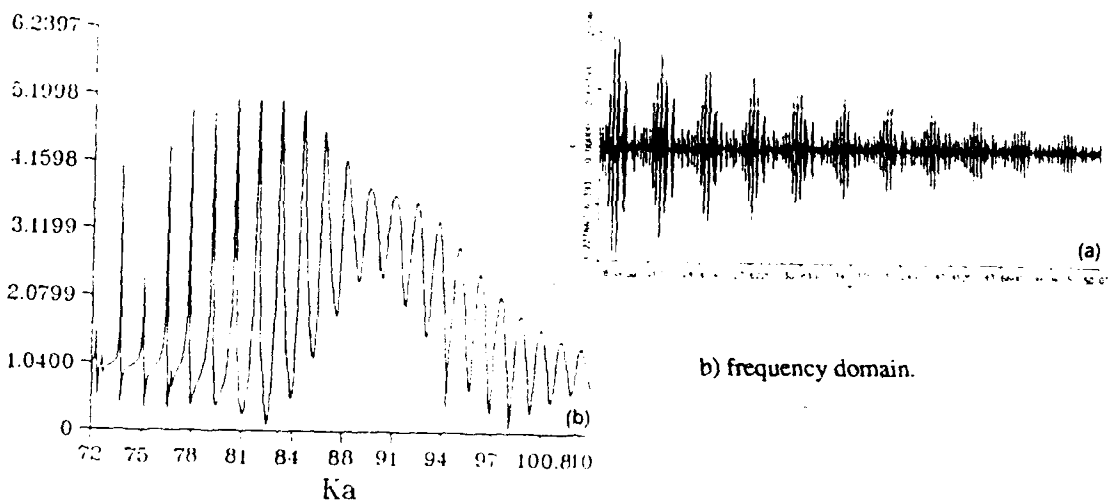
The above analysis dealt with pseudo-Stoneley waves. There is another phenomenon due to waves that have phase velocities that correspond to about the speed of sound in water. They are not, however, sharply defined in partial wave space, nor are they associated with the flexural wave at coincidence frequency. They are associated with the density of the material, and the thickness (really just the mass of the target) and the frequency. Their importance increases with frequency and they do not manifest themselves as sharp resonances in the form function

but rather wash-out other resonances such as the S_0 and A_0 resonances. Thus for light material and thin shells such as Aluminum and at high frequency one does not observe sharp resonances due to this wash out effect. Figs. 8 and 9 illustrate this effect in partial wave space for Aluminum of 2.5%, and an Aluminum shell of 5% at a ka of 250. It is clear that there is a prominent contribution in each case corresponding to a phase velocity equal to the speed of sound in water (it is centered about 250 indicative of a slightly subsonic wave). The other peaks correspond to the Lamb waves. Clearly, the effect is more pronounced for thinner (lighter materials) shells. In Fig. 10 we illustrate a plot of the phase velocity of this wave for the 5% steel case. An extensive study of this phenomena is to be presented in a future work including the sensitivity to material properties and the overall effect on the form function.



b) frequency domain.

Fig. 6 Scattering from 1% steel shell a) Time domain,

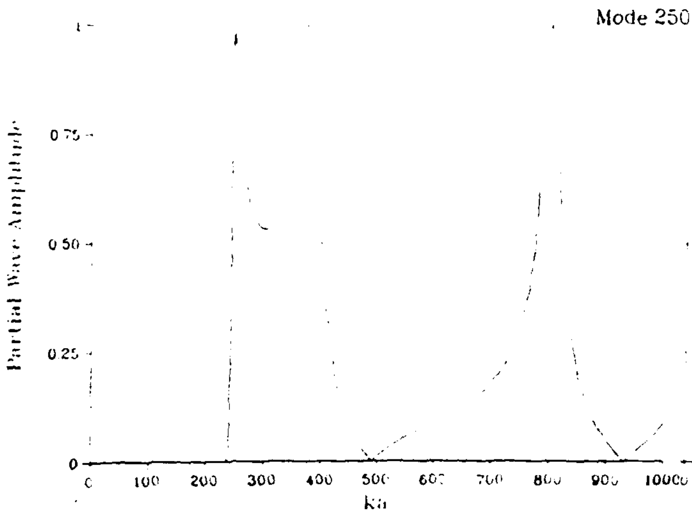


b) frequency domain.

Fig. 7 Scattering from 1% WC shell a) Time domain,

Conclusions

We have used the new acoustic back ground for an elastic shell, partial wave analysis and a time domain version of resonance scattering theory to discuss several interesting resonances recently under study. One can see how use of these tools along with analogies with flat plate results enable one to infer the nature of such complicated phenomena. The fact that several competing events can occur in the same frequency region perhaps renders the direct measurement of surface vibrations less useful then an inferential approach. On the other hand an inference does not guarantee that that inferred is always the correct interpretation.



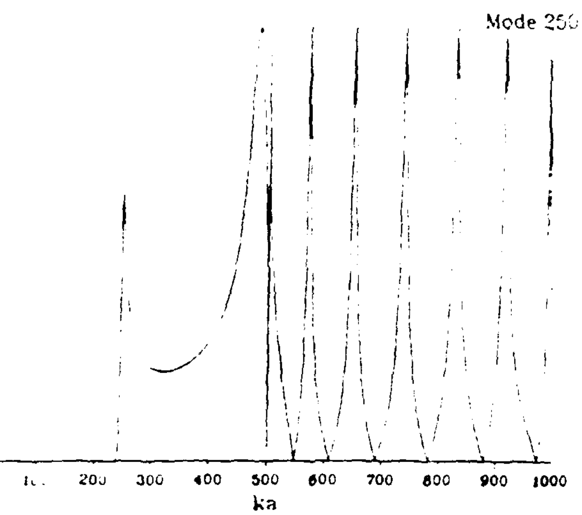


Fig. 8 Full partial Wave Analysis for 2.5% Aluminum Shell.

Fig. 9 Full partial Wave Analysis for 5% Aluminum Shell.

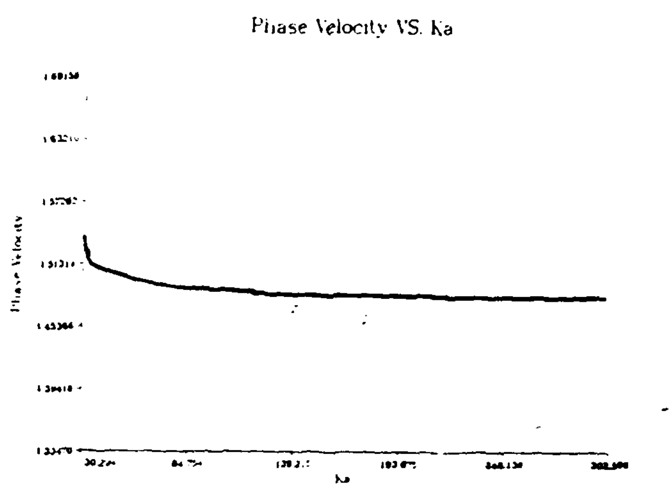


Fig.10 Phase velocity for pure water borne resonance.

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